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Cover-Crop Systems Affect Weed Communities in a California Vineyard

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Vineyard weed communities were examined under four dormant-season cover-crop systems representative of those used in the north-coastal grape-growing region of California: no-till annuals (ANoT) (rose clover, soft brome, zorro fescue), no-till perennials (PNoT) (blue wildrye, California brome, meadow barley, red fescue, yarrow), tilled annual (AT) (triticale), and a no-cover-crop tilled control (NoCT). Treatments were carried out for 3 yr in the interrows of a wine grape vineyard. Glyphosate was used to control weeds directly beneath the vines, in the intrarows. Treatments significantly impacted weed biomass, community structure, and species diversity in the interrows. Orthogonal contrasts showed that tillage, and not the presence of a cover crop, impacted interrow weed biomass. Distance-based redundancy analyses (db-RDA) revealed significant effects of the cover-crop systems and of tillage on weed community structure in the interrows. For scarlet pimpernel and spiny sowthistle, the combination of ANOVA and orthogonal contrasts confirmed their association with the tilled treatments, as revealed by db-RDA. This same approach identified the association between California burclover and the no-till treatments. Our findings of no significant effects of the cover-crop systems on weed biomass, community structure, or diversity in the intrarows demonstrate that the impacts the cover-crop management systems had on the interrows did not carry over to adjacent intrarows. In addition, the fact that the cover crops did not affect vine yield, growth, or nutrition relative to the no-cover-crop control suggests that cover crops are likely to minimize soil erosion from winter rains, which is the primary purpose of vineyard cover cropping in northern California, without adversely affecting vine health or weed control.

Nomenclature: Glyphosate; blue wildrye, *Elymus glaucus* Buckley ELYGL; California brome, *Bromus carinatus* Hook. & Arn. BROCN; California burclover, *Medicago polymorpha* L. MEDPO; meadow barley, *Hordeum brachyantherum* Nevski HORBR; red fescue, *Festuca rubra* L. FESRU; rose clover, *Trifolium hirtum* All. TRH14; scarlet pimpernel, *Anagallis arvensis* L. ANGAR; soft brome, *Bromus hordeaceus* L. BROMO; spiny sowthistle, *Sonchus asper* (L.) Hill SONAS; triticale, X *Triticosecale rimpaui* Wittm. TRITI; yarrow, *Achillea millefolium* L. AMARE; zorro fescue, *Vulpia myuros* (L.) K. C. Gmel. VLPMY; wine grape, *Vitis vinifera* L. 'Merlot'.

Key words: Grapevine, integrated weed management, perennial cropping system, sustainable vineyard floor management, tillage.

A growing list of herbicide-resistant weeds (Heap 2005) reinforces the concept that repeated use of a single tactic for pest control may not only facilitate infestations of the most problematic species, but may fundamentally change population genetics. Integrated weed management (IWM) aims, in part, to prevent infestations of species that are most difficult to control by stressing the use of multiple tactics that collectively address the causes of weed problems, rather than simply reacting to infestations (Buhler 2002). This approach can begin with individual practices, and is meant to eventually progress into a set of strategies that combine weed control practices (e.g., herbicides, mechanical cultivation) with crop production practices known to alter weed communities (e.g., crop rotation, irrigation; Liebman and Gallandt 1997). For example, tillage and planting suites of cover-crop species (e.g., perennial bunchgrasses, N-fixers) with distinct traits (e.g., plant architecture, seed bank longevity) can cause differential shifts in weed communities (Shrestha et al. 2002; Townsend and Hildrew 1994).

The principles of IWM have been examined primarily in annual cropping systems (e.g., Sutton et al. 2006). Adapting such principles to perennial crops is challenging, however, because weed control is focused on portions of the field planted to the crop. This is true in California wine grape vineyards, where herbicides are typically applied to control weeds directly beneath the trellis system, in the intrarows, where the most problematic weeds are those that grow into the canopy and disrupt harvest. The portion of the vineyard floor in between the intrarows, the interrows, is managed not with weed control as the main priority, but with a focus on soil erosion and nutrition management through cover cropping and/or tillage. Nonetheless, such practices have been shown to influence weed communities in annual systems (Moonen and Barberi 2004; Teasdale et al. 1991). A recent report of their influence on vineyard weed communities in the interrows (Gago et al. 2007) highlights the need for investigation of how cover-cropping practices interact with weed control practices in spatially distinct and differently managed portions of the vineyard floor. Understanding how such nonchemical weed control strategies impact weed communities may decrease the need for herbicides, and may improve the sustainability of California wine grape production systems.

The aim of our research was to evaluate the composition and diversity of vineyard weed communities in a northern California wine grape vineyard, under the influence of four cover-crop systems: a no-till mixture of an annual legume and annual grasses (rose clover, soft brome, zorro fescue), a no-till mixture consisting predominantly of perennial bunchgrasses (California brome, blue wildrye, red fescue, meadow barley, yarrow), a tilled cereal (triticale), and a no-cover-crop tilled treatment in which resident vegetation was tilled. Such dormant-season cover crops are typically planted in California vineyards to minimize runoff from winter rains (McGourty and Christensen 1998), but the practice of maintaining a cover crop that provides additional benefits (e.g., enhancing vine mineral nutrition; Patrick et al. 2004; Patrick-King and Berry 2005) is gaining popularity as a sustainable production practice. We also monitored vine yield and growth, and soil mineral nutrition and physical properties, as previous research has documented significant effects of some cover crops on

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such parameters (Ingels et al. 2005; Patrick-King and Berry 2005; Tesic et al. 2007).

We tested the hypotheses that the cover-crop systems affect weed biomass, community structure, and diversity in vineyard interrows and intrarows. Based on past research demonstrating an inverse relationship between cover-crop biomass and weed biomass in annual cropping systems (Barberì and Mazzoncini 2001; Ngouajio and McGiffen 2002), we were curious to determine if cover crops in the interrows could compete with weeds successfully, as cover-crop residues have been shown to decrease light penetration and temperature at the soil surface, thereby suppressing germination of some species (Dyer 1995). Furthermore, if the cover-crop treatments could compete weeds in the interrows successfully, we thought it might be possible for them to have a concomitant influence on the dispersal of weeds from the interrows to the intrarows. In cases in which cover-cropping systems did affect weed community structure, we were interested in determining if all weed species responded similarly or if certain species were favored by certain treatments.

Materials and Methods

The experiment was conducted in a commercial wine grape vineyard in the Napa Valley of northern California from 2002 to 2005. The vineyard was established in 1996 with Merlot (clone 314) on 110R rootstock (*V. berlandieri* Planch. × *V. rupestris* Scheele). Vine spacing was 1.8×1.8 m^2, with east–west row orientation. Vines were trained as unilateral cordons to a vertical shoot positioning trellis system. The 0.84-m–wide section of soil in the intrarow was level with the soil in the interrows; vines were not elevated on berms. The vineyard was on Bale soil (fine–loamy, mixed, thermic Cumulic Ultic Haploxeroll). In a separate section of this same vineyard, which covers a total of 9.6 ha, we previously examined grapevine root distribution (Cheng and Baumgartner 2005) and alternative intrarow weed control practices (Baumgartner et al. 2007). Prior to the start of the experiment, in October 2002, interrows of the entire vineyard were maintained as no till, with a cover crop of zorro fescue that was planted in 1999. To kill the zorro fescue, in preparation for our experiment, interrows were sprayed with glyphosate (5.6 kg ae vineyard ha^{-1}) and the dead zorro fescue was disked.

The four cover-crop treatments were applied to the interrows: annual–no till (ANoT), annual–till (AT), perennial–no till (PNoT), and no-cover-crop–till (NoCT). ANoT was planted with a mixture of rose clover, soft brome, and zorro fescue (all self-seeding annuals) at a combined rate of 25 kg vineyard ha^{-1} (seed composition by weight: 30% rose clover, 30% soft brome, 40% zorro fescue). AT was planted with triticale (annual cereal) at a rate of 55 kg vineyard ha^{-1}. PNoT was planted with a mixture of blue wildrye, California brome, meadow barley, red fescue (all perennial bunchgrasses), and yarrow (perennial forb) at a combined rate of 35 kg vineyard ha^{-1} (seed composition by weight: 7.5% yarrow, 18.5% blue wildrye, 18.5% California brome, 18.5% meadow barley, 37% red fescue). NoCT was not seeded with a cover crop; resident vegetation was allowed to colonize this treatment. All cover crops were planted at the start of the experiment (October 27, 2002) with a 0.96-m–wide seed drill to a soil depth of approximately 1 cm, after disking the interrow soil to a depth of approximately 15 cm to prepare the seed bed. AT was reseeded with the seed drill annually (October 24, 2003; October 28, 2004), with the same soil preparation as in the first year of planting. The tilled treatments, AT and NoCT, were tilled once per year (June 9, 2003; May 15, 2004; April 4, 2005) with a disk at a soil depth of approximately 15 cm. Cover-crop mixtures, planting rates, tillage timing and depth, and seed-bed preparation were carried out according to standard vineyard practice (Ingels et al. 1998). The species mixtures for ANoT and PNoT are used by growers in the North Coastal grape-growing region of northern California. ANoT and PNoT are primarily used in hillside vineyards to prevent soil erosion during winter rains. AT and NoCT are more common in flat vineyards, where risk of soil erosion is low.

Cover-crop treatments were imposed on 48 adjacent intrarows. Although the treatments were extended along the entire length of the interrows, data (weed and cover-crop biomass, vine and soil mineral nutrition, vine yield and growth) were collected only from the eastern ends, between the 11th and 50th vines. Treatments were arranged in a randomized complete block design with four blocks (0.27 ha^2 per block), and one treatment replicate per block. Treatments were applied to three consecutive interrows; data were collected from the central interrow and the immediately adjacent intrarow to the north.

In the intrarows, glyphosate[1] was applied with a tractor-mounted, 1.2-m-wide, boom sprayer with two fan-type nozzles directed beneath the vines on both sides of the tractor. Glyphosate was applied twice per year according to standard vineyard practice: once before bud break at a rate of 2.8 kg vineyard ha^{-1} (February 22, 2003; January 1, 2004; February 11, 2005), and once after the removal of trunk suckers in late spring, at a rate of 5.6 kg vineyard ha^{-1} (May 22, 2003; April 27, 2004; May 13, 2005).

Temperature and precipitation were recorded by the nearest California Irrigation Management Information System (CIMIS) weather station (Oakville Station No. 77; Baumgartner et al. 2007). The combination of infrequent drip irrigation (85 kl ha^{-1} applied once per week, July to October) and rare summer precipitation meant that weed pressure was highest in spring, when high soil moisture and temperature encourage plant growth. Collection of aboveground biomass of both weeds and cover crops was timed in between the last glyphosate application and the end of the rainy season, and was based on visual observation of peak weed height and cover-crop seed set (June 4, 2003; May 12, 2004; May 31, 2005). This time period coincided with full bloom in the grapevines. Biomass in the intrarows was collected from four randomly placed, 25×40–cm quadrats per treatment per block (two at the base of vine trunks, two between adjacent vines). Biomass in the interrows was collected from four randomly placed quadrats per treatment per block (two at the center of the interrows, two at the edge of the interrows and adjacent to the sampled intrarow). Plants were sorted by species, dried (70 C, 7 d), and weighed. Filaree species [broadleaf filaree (*Erodium botrys* (Cav.) Bertol), redstem filaree [*E. cicutarium* (L.) L'Her. Ex Ait.], whitestem filaree (*E. moschatum* (L.) L'Her. Ex Ait.)] were difficult to distinguish from one another, and were combined under *Erodium* spp.

Grape leaf petioles and vineyard soil for analyses of mineral composition were collected at full bloom (June 5, 2003; June 1, 2004; May 26, 2005). From each row, 100 petioles were collected by a standard sampling procedure (Winkler et al. 1965), pooled, dried (70 C, 7 d), ground, and analyzed for total nitrogen (N), total phosphorus (P), total potassium (K), zinc (Zn), and boron (B) (DANR Laboratories, University of California, Davis, CA). Soil was collected from four random locations per replicate intrarow and four per replicate interrow, with a 4.6-cm-diameter auger to a depth of 15 cm, pooled, dried (70 C, 7 d), ground, and analyzed for NH_4-N, NO_3-N, Olsen-P, exchangeable K (X-K), exchangeable sodium (X-Na), exchangeable calcium (X-Ca), exchangeable magnesium (X-Mg), cation exchange capacity (CEC), organic matter (OM), and pH. Fruit clusters were harvested (September 19, 2003; September 28, 2004; October 25, 2005) from six adjacent vines per intrarow. Pruned dormant shoots were weighed (November 27, 2003; November 22, 2004; December 12, 2005) from the same vines.

Species richness (S) and diversity (Shannon's diversity, H') were calculated separately for intrarows and interrows in PC-ORD,[2] with the use of the following formula (Ludwig and Reynolds 1988):

$$S = \text{number of nonzero elements in a treatment}$$

$$H' = -\sum_{i}^{s} p_i \log pi,$$

where p_i is the proportion of s made up of the ith species. For H', the treatment with the highest value has a higher S, has more species present in equal abundance than the other treatments, or both. S and H' were averaged across the four quadrats per location (intrarow or interrow) per treatment per block. Cover crops were not included, so as not to inflate S or H' artificially. To accommodate samples with no weeds, 0.0001 g m^{-2} was added to all samples for filaree, the species found in every block, treatment, and year. Despite the application of glyphosate to all interrows at the start of the experiment to kill zorro fescue, the former cover crop, it persisted in all treatments and was considered a weed in all treatments other than the one it was planted in, ANoT.

Analyses of variance (ANOVAs) were used to determine the effects of treatment and year on weed and cover-crop biomass, species richness and diversity, vine mineral nutrients, soil chemical and physical properties, grape yields, and pruning weights. ANOVAs were performed with the use of the MIXED procedure in SAS,[3] with Kenward–Roger as the denominator degrees-of-freedom method (Littell et al. 1996). Year was considered a repeated measure, block and block interactions were random effects, and treatment, year, and treatment × year were fixed effects. To satisfy the assumption of homogeneity of variance, the following transformations were applied: $\log_{10}$ transformations to weed and cover-crop biomass and petiole Zn; square-root transformations to vine pruning weights and petiole P; and rank transformations to soil Olsen-P, OM, X-K, and CEC. For significant effects ($P < 0.05$), differences among treatment means were assessed by comparison of 95% confidence intervals, such that means without overlapping intervals were considered significantly different (Westfall et al. 1999). Backtransformed geometric means and 95% confidence limits are presented, for ease of interpretation.

Orthogonal contrasts were used to test the effects of tillage and the presence of a cover crop on weed biomass and diversity, when ANOVA showed a significant treatment effect or treatment × year interaction. For parameters affected by a significant treatment effect with no significant treatment × year interaction in ANOVA, contrast statements were used in the MIXED procedure to make the following treatment comparisons: NoCT versus all treatments with a planted cover crop (ANoT, AT, PNoT); and the tilled treatments (NoCT, AT) versus the no-till treatments (ANoT, PNoT). To make the same treatment comparisons for parameters affected by a significant treatment × year interaction, least squares mean estimate statements were used in the GLIMMIX procedure in SAS,[3] and were carried out separately for each year.

Distance-based redundancy analysis (db-RDA) was used to evaluate treatment effects on weed community structure (Legendre and Anderson 1999). Analyses were based on aboveground biomass of weed species present in ≥ 10% of intrarow and interrow samples. Species omitted from analyses were present in fewer than 10 of 96 total samples collected over the entire experiment. Interrows and intrarows were analyzed separately. Cover crops were omitted from the analyses. To accommodate samples with zero biomass, 0.0001 g m^{-2} was added to all samples for filaree, the species that was present in every block, treatment, and year. Analyses were performed in CANOCO[4] (Leps and Smilauer 2003). The raw biomass data were first converted into a Euclidean distance matrix with the PrCoord program in CANOCO. Reduced model permutation testing was then used to determine the significance of the main effect of treatment (all four cover-crop systems treated separately) or tillage (treatments grouped according to presence/absence of tillage; NoCT + AT versus ANoT + PNoT); block and year effects were removed through partial ordination and the main plots were treated as the exchangeable units.

For db-RDA analyses that revealed a significant effect of treatment on community structure, treatment centroids and species with a > 25% correlation to either ordination axis were displayed in biplots. Proximity of a species arrow endpoint to a treatment centroid indicates that the species played an important role in distinguishing that treatment. Species identified as having a strong association with a given treatment through db-RDA were further investigated on an individual basis in ANOVA, with the use of the MIXED procedure in SAS.[3] This approach of coupling multivariate analysis, specifically db-RDA, with univariate analysis is described in detail by Reberg–Horton et al. (2006). In ANOVA following db-RDA, year was considered a repeated measure, block and block interactions were random effects, and treatment, year, and treatment × year were fixed effects. To satisfy the assumption of homogeneity of variance, $\log_{10}$ transformations were applied to species biomass. For significant effects ($P < 0.05$), differences among treatment means were assessed by comparison of 95% confidence intervals, such that means without overlapping intervals were considered significantly different (Westfall et al. 1999). Backtransformed geometric means and 95% confidence limits are presented, for ease of interpretation. When ANOVA identified a significant treatment or treatment × year interaction on species biomass, orthogonal contrasts were used to test the effects of tillage on species biomass, as described above for total weed biomass.

Results and Discussion

Weed and Cover-Crop Biomass. The cover-crop systems did not affect weed biomass in the intrarows ($P = 0.07$), where

Table 1. Vineyard floor biomass (weeds and cover crops).[a,b]

Treatments		Intrarows Weed	Intrarows Cover crop	Interrows Weed	Interrows Cover crop
		Biomass (g m^{-2})			
2003	NoCT	2.2 a	0.0 a	1.1 a	0.0 a
	AT	12.4 a	0.5 ab	6.6 ab	180.0 c
	ANoT	20.6 a	3.6 c	26.4 bc	228.1 c
	PNoT	32.3 a	1.5 bc	157.7 c	49.8 b
2004	NoCT	1.8 a	0.0 a	2.2 a	0.0 a
	AT	4.3 a	0.0 a	0.7 a	2.1 b
	ANoT	4.3 a	0.6 a	6.4 ab	93.6 c
	PNoT	8.8 a	0.1 a	22.3 b	41.9 c
2005	NoCT	4.2 a	0.0 a	184.0 a	0.0 a
	AT	3.1 a	0.0 a	135.0 a	124.3 b
	ANoT	3.2 a	0.2 a	182.8 a	439.7 c
	PNoT	3.9 a	0.1 a	122.0 a	101.9 b

[a] Abbreviations: NoCT, no cover crop, tilled; AT, annual cover crop, till; ANoT, annual cover crop, no-till; and PNoT, perennial cover crop, no-till.
[b] Means ($n = 4$) followed by different letters in the same column and year are significantly different at P $\leq$ 0.05, based on nonoverlapping 95% confidence intervals for mean weed biomass or mean cover-crop biomass.

weed biomass was consistently low in all years (Table 1). Cover-crop systems did affect cover-crop biomass, but only in 2003 (treatment $\times$ year, P = 0.02). Cover crops were found in the intrarows adjacent to all treatments with a cover crop (ANoT, AT, PNoT) in 2003, and were present only in intrarows adjacent to the no-till treatments (ANoT, PNoT) in 2004 and 2005. Nonetheless, cover-crop biomass in the intrarows was extremely low, with only 2 of 12 treatment means registering above 1 g m^{-2}. An aspect of cover cropping that is of concern to grape growers is competition between cover crops and vines, especially that which leads to severe water stress. However, it seems unlikely in our experiment that unintended dispersal of cover crops to the intrarows, where they might compete with vines more so than when restricted to the interrows, would result in vine water stress because cover-crop biomass was always lower than weed biomass (Table 1). Our finding of no significant effects of the cover-crop systems on weed biomass in the intrarows suggests that the presence of a cover crop in the interrows is unlikely to affect total weed biomass under the vines, as long as intrarows are treated with herbicides.

The cover-crop systems affected weed biomass in the interrows (significant treatment $\times$ year, P < 0.0001). Weed biomass varied among treatments in 2003 and 2004, but did not vary in 2005, when weed biomass increased substantially in all interrows (Table 1), likely due to increased winter rainfall of 25 cm relative to the previous year (Baumgartner et al. 2007). In 2003 and 2004, the tilled treatments (NoCT and AT) had significantly lower weed biomass than the no-till treatments (PNoT and ANoT). Not surprisingly, cover-crop biomass varied among interrow treatments, and differences were inconsistent over time (significant treatment $\times$ year, P < 0.0001). As with the 2005 increase in weed biomass, there was a similar increase in cover-crop biomass for all interrows with a planted cover crop (Table 1). ANoT had the highest cover-crop biomass each year; this was the only cover crop that maintained a uniformly thick canopy in the interrows. Compared to the cover-crop biomass of the reseeding annual grasses in ANoT, that of the perennial grasses in PNoT was relatively sparse. Temporal changes in cover-crop biomass of AT, which followed somewhat similar trends to that of ANoT, were especially dramatic in 2004, when poor establishment of triticale, the cover crop for this treatment, coincided with a very dry winter.

Cover-crop biomass in ANoT interrows was always higher than weed biomass, ranging from 15 times to twice that of weed biomass (Table 1). Our finding of greater cover-crop biomass relative to weed biomass in ANoT is consistent with that of previous studies on cover crops in annual cropping systems (Barberì and Mazzoncini 2001; Ngouajio and McGiffen 2002). Lack of a consistent relationship between cover-crop and weed biomass in AT and PNoT is likely due to a combination of poor cover-crop establishment in certain years and a sparse canopy. With no irrigation in the interrows, the cover crops depended primarily on winter rains for soil moisture. It is possible that both the sparse spatial arrangement and the thin canopy of grass foliage in PNoT allowed for open spaces where weeds could colonize or germinate from the seed bank, based on similar observations in restored perennial grasslands (Potthoff et al. 2005).

In spite of the consistent inverse relationship between cover-crop and weed biomass, ANoT interrows did not have the lowest weed biomass (Table 1). In fact, orthogonal contrasts showed that interrow weed biomass was higher in the no-till treatments compared to the tilled treatments in 2003 and 2004 (P < 0.0001 and P < 0.0001, respectively), the years in which weed biomass varied significantly according to ANOVA (P < 0.0001). In comparison, the contrast of NoCT versus all treatments with a planted cover crop (AT, ANoT, PNoT) were not significant in 2003 or 2004 for interrow weed biomass (P = 0.9 and P = 0.3, respectively). Therefore, it seems that tillage had a relatively greater effect on weed biomass than did competition from a cover crop.

Weed Communities. Annual, broad-leaved weeds dominated the weed flora in the intrarows and interrows (Tables 2 and 3). Interrows had more total species than intrarows, with both having a similar relative proportion of annuals to perennials (excluding cover crops, 27 : 4 in interrows and 20:5 in intrarows). The few perennial weeds [buckhorn plantain (*Plantago lanceolata* L.), curly dock (*Rumex crispus* L.), field bindweed (*Convolvulus arvensis* L.), volunteer grape, white

Table 2. Species in vineyard intrarows. Each value is the mean of four observations, averaged across blocks. Zero biomass is represented by a dash.[a]

		Treatment											
		NoCT			AT			ANoT			PNoT		
Species	Common name	2003	2004	2005	2003	2004	2005	2003	2004	2005	2003	2004	2005
		Relative abundance (species biomass/sample biomass × 100)											
Weeds													
Amaranthus retroflexus L.	Redroot pigweed	–	0.09	–	–	–	–	0.80	0.07	–	–	–	–
Anagallis arvensis L.	Scarlet pimpernel	–	20.70	34.29	1.59	–	11.00	–	–	–	2.99	5.21	2.19
Brassica rapa L.	Birdsrape mustard	–	1.12	–	–	0.20	–	2.28	0.31	–	–	1.15	–
Calendula arvensis L.	Field marigold	–	0.22	–	6.05	0.12	–	4.31	–	–	3.24	1.39	19.62
Chamaesyce maculata (L.) Small	Spotted spurge	–	–	–	–	–	–	–	0.62	–	–	–	–
Chenopodium album L.	Common lambsquarters	–	–	–	32.53	0.12	0.20	19.35	7.08	2.15	1.63	–	11.06
Convolvulus arvensis L.	Field bindweed	0.28	0.56	–	0.16	3.09	–	–	–	0.56	0.10	4.83	0.42
Epilobium brachycarpum C. Presl	Panicle willowherb	97.59	25.41	–	21.30	64.64	11.00	37.82	1.43	–	62.37	4.08	12.00
Erodium spp.	Filaree	–	48.24	5.80	9.58	30.26	22.59	0.83	37.50	64.86	6.06	35.07	13.67
Geranium carolinianum L.	Carolina geranium	–	–	8.13	–	–	4.52	–	6.62	13.22	–	7.98	24.22
Kickxia spuria (L.) Dumort.	Female fluvellin	–	–	–	2.70	–	5.50	12.76	0.40	–	1.69	10.72	2.61
Lythrum hyssopifolia L.	Loosestrife	–	–	7.58	–	0.12	29.47	0.24	6.89	12.99	1.15	2.10	2.09
Medicago polymorpha L.	California burclover	–	–	–	–	0.57	–	–	4.66	–	–	0.42	–
Plantego lanceolata L.	Buckhorn plantain	–	–	–	6.22	–	–	–	–	–	–	–	–
Polygonum arenastrum Boreau	Common knotweed	–	–	–	–	–	–	0.33	–	–	–	–	–
Raphanus raphanistrum L.	Wild radish	–	–	–	–	–	–	–	1.24	–	–	0.78	–
Rumex crispus L.	Curly dock	–	3.35	0.87	0.89	–	–	0.57	0.20	1.58	0.11	1.63	5.01
Senecio vulgaris L.	Common groundsel	–	–	–	5.15	–	15.72	3.59	0.75	–	–	1.24	4.38
Sonchus asper (L.) Hill	Spiny sowthistle	–	–	–	0.19	0.06	–	–	0.05	0.45	–	11.24	–
Sonchus oleraceus L.	Annual sowthistle	–	–	–	–	–	–	–	13.18	–	–	0.73	–
Trifolium repens L.	White clover	–	–	42.96	–	–	–	–	–	–	–	–	–
Veronica persica Poir.	Persian speedwell	–	–	–	–	–	–	0.23	–	–	–	–	–
Veronica peregrina L.	Purslane speedwell	–	0.30	–	–	–	–	–	–	–	–	–	–
Vicia sativa L.	Common vetch	–	–	–	–	–	–	0.69	6.30	–	–	–	–
Vitis vinifera L. 'Merlot'	Volunteer grape	2.12	–	0.38	4.34	0.18	–	0.21	0.63	0.90	0.51	6.38	1.57
Cover crops[b]													
Bromus carinatus H. & A.	California brome	–	–	–	2.81	–	–	–	–	–	3.41	–	0.21
Bromus hordeaceus L.	Soft brome	–	–	–	–	–	–	10.01	0.50	–	–	–	–
Elymus glaucus Buckley	Blue wildrye	–	–	–	–	–	–	–	–	–	0.91	–	0.73
Festuca rubra L.	Red fescue	–	–	–	–	–	–	–	–	–	0.55	0.92	0.21
Trifolium hirtum All.	Rose clover	–	–	–	–	–	–	–	0.29	–	–	–	–
X *Triticosecale rimpaui* Wittm.	Triticale	–	–	–	6.48	–	–	–	–	–	–	–	–
Vulpia myuros var. *hirsuta* Hack.	Zorro fescue	–	–	–	–	0.65	–	5.99	11.30	3.28	15.27	4.13	–

[a] Abbreviations: NoCT, no cover crop, tilled; AT, annual cover crop, till; ANoT, annual cover crop, no-till; and PNoT, perennial cover crop, no-till.
[b] Cover-crop treatments, which were planted in the adjacent interrows, consisted of the following species: soft brome, rose clover, and zorro fescue (ANoT), triticale (AT), no planted cover crop (NoCT), and yarrow, California brome, blue wildrye, red fescue, and meadow barley (PNoT).

Table 3. Species in vineyard interrows. Each value is the mean of four observations, averaged across blocks. Zero biomass is represented by a dash.[a]

Species	Common name	NoCT 2003	NoCT 2004	NoCT 2005	AT 2003	AT 2004	AT 2005	ANoT 2003	ANoT 2004	ANoT 2005	PNoT 2003	PNoT 2004	PNoT 2005
		Relative abundance (species biomass/sample biomass × 100)											
Weeds													
Anagallis arvensis L.	Scarlet pimpernel	–	–	2.65	–	–	0.12	–	–	–	–	0.05	0.05
Avena fatua L.	Wild oat	–	–	0.13	–	–	0.44	–	–	0.29	–	–	–
Brassica rapa L.	Birdsrape mustard	100.00	3.15	–	1.46	–	0.12	0.47	–	0.08	15.97	–	–
Bromus diandrus L.	Ripgut brome	–	–	–	–	–	–	–	–	0.19	–	–	0.48
Calandrinia ciliata	Redmaids	–	2.50	0.09	–	–	0.26	–	0.03	–	–	–	–
(Ruiz Lopez & Pavon) DC.													
Calendula arvensis L.	Field marigold	–	12.35	0.89	0.26	6.56	2.70	0.07	0.13	0.01	8.86	5.84	0.70
Convolvulus arvensis L.	Field bindweed	–	3.02	–	–	0.18	–	0.08	–	0.02	–	–	–
Conyza canadensis (L.) Cronq.	Horseweed	–	–	–	–	–	–	–	–	–	–	–	0.02
Epilobium brachycarpum C. Presl	Panicle willowherb	–	36.44	1.23	8.16	–	0.52	8.54	0.20	–	35.69	0.40	0.03
Erodium spp.	Filaree	–	21.46	4.76	–	1.07	1.87	–	0.37	1.20	2.00	6.45	1.14
Geranium carolinianum L.	Carolina geranium	–	–	3.80	–	1.22	1.22	–	0.80	0.51	0.06	6.30	1.13
Gnaphalium purpureum L.	Purple cudweed	–	–	–	–	–	–	–	–	–	–	–	0.05
Juncus bufonius L.	Toad rush	–	–	0.59	–	–	0.46	–	0.01	–	–	–	0.10
Kickxia spuria (L.) Dumort.	Female fluvellin	–	–	–	–	–	0.33	–	–	–	0.21	–	0.14
Lactuca serriola L.	Prickly lettuce	–	–	0.98	–	–	0.11	–	0.07	0.04	–	–	–
Lolium multiflorum Lam.	Italian ryegrass	–	–	9.37	–	–	–	2.17	0.21	0.28	–	0.45	0.67
Lythrum hyssopifolia L.	Loosestrife	–	–	1.45	–	–	0.62	–	0.11	–	0.01	0.02	0.16
Medicago polymorpha L.	California burclover	–	–	3.97	–	–	7.76	2.48	2.40	21.91	–	–	24.60
Poa annua L.	Annual bluegrass	–	–	0.26	–	–	0.16	–	0.10	0.03	–	0.15	0.07
Polygonum arenastrum Boreau	Common knotweed	–	–	0.01	–	–	–	–	–	–	–	0.04	–
Ranunculus muricatus L.	Buttercup	–	–	1.44	–	–	–	–	0.02	0.34	–	7.99	1.14
Rumex crispus L.	Curly dock	–	–	0.02	0.28	0.24	–	–	0.02	–	2.20	–	–
Senecio vulgaris L.	Common groundsel	–	–	–	–	–	–	–	–	–	–	–	0.08
Sonchus asper (L.) Hill	Spiny sowthistle	–	–	2.69	–	–	2.76	–	–	0.09	–	0.43	0.03
Sonchus oleraceus L.	Annual sowthistle	–	–	0.89	–	–	0.34	–	–	0.01	–	–	–
Spergula arvensis L.	Corn spury	–	–	–	–	–	–	–	–	–	0.33	–	–
Trifolium repens L.	White clover	–	–	31.65	–	–	9.43	–	–	0.58	–	–	0.02
Veronica persica Poir.	Persian speedwell	–	–	0.01	–	–	–	–	–	–	–	–	–
Veronica peregrina L.	Purslane speedwell	–	–	0.01	–	–	–	–	–	–	–	–	0.01
Vicia sativa L.	Common vetch	–	–	0.41	–	–	–	–	2.65		–	–	–
Vitis vinifera L. 'Merlot'	Volunteer grape	–	–	–	–	–	0.02	–	–	0.02	–	–	0.01
Cover crops[b]													
Achillea millefolium L.	Yarrow	–	–	–	–	–	–	–	–	–	0.25	–	0.01
Bromus carinatus H. & A.	California rome	–	–	–	–	–	–	–	–	–	11.98	13.20	19.80
Bromus hordeaceus L.	Soft brome	–	–	–	–	–	–	35.78	85.53	17.30	–	–	–
Elymus glaucus Buckley	Blue wildrye	–	–	–	–	–	–	–	–	–	4.51	2.90	4.99
Festuca rubra L.	Red fescue	–	–	–	–	–	–	0.35	–	–	3.03	44.90	3.61
Hordeum brachyantherum Nevski	Meadow barley	–	–	0.54	–	–	–	–	–	–	6.31	3.11	17.38
Trifolium hirtum All.	Rose clover	–	–	–	–	13.06	0.84	42.92	0.50	55.35	–	4.09	–
X *Triticosecale rimpaui* Wittm.	Triticale	–	–	–	89.02	77.08	49.98	–	–	–	–	–	–
Vulpia myuros var. *hirsuta* Hack.	Zorro fescue	–	21.09	32.17	0.82	0.59	19.96	7.14	6.85	1.41	8.59	3.69	23.59

[a] Abbreviations: NoCT, no cover crop, tilled; AT, annual cover crop, till; ANoT, annual cover crop, no-till; and PNoT, perennial cover crop, no-till.
[b] Cover-crop treatments consisted of the following species: soft brome, rose clover, and zorro fescue (ANoT), triticale (AT), no planted cover crop (NoCT), and yarrow, California brome, blue wildrye, red fescue, and meadow barley (PNoT).

clover (*Trifolium repens* L.)] had low frequencies and/or inconsistent occurrence, which made it difficult to identify their species–treatment associations.

The db-RDA analyses revealed significant effects of the cover-crop systems on weed community structure when the systems were treated as four separate treatments ($P = 0.02$) or grouped according to tillage ($P = 0.04$). In both interrow analyses, treatments were distinguished by the same six species: California burclover, field marigold (*Calendula arvensis* L.), filaree species (*Erodium* spp.), panicle willowherb (*Epilobium brachycarpum* C. Presl), scarlet pimpernel, and spiny sowthistle (Figure 1). ANOVA revealed significant treatment and treatment × year effects on biomass of all six species (Figure 2), and orthogonal contrasts showed significant biomass differences in till versus no-till treatments in at least one study year (Table 4).

Species–treatment associations in the interrows, as revealed by db-RDA (Figure 1), were verified by ANOVA and orthogonal contrasts for three of the six species that had > 25% correlation with either axis in the species-treatment biplots. For example, spiny sowthistle was favored by tillage, based on the proximity of this species' arrow endpoint to NoCT and AT or 'Till' in both biplots (Figure 1), based on significant treatment and treatment × year effects in ANOVA (Figure 2), and based on significantly higher biomass in till versus no-till treatments (Table 4). Spiny sowthistle was present in all treatments in 2005, when it had higher biomass (Figure 2) and higher relative abundance in both NoCT and AT interrows (Table 3). Scarlet pimpernel was also favored by tillage, based on db-RDA (Figure 1), ANOVA (Figure 2), and the till versus no-till contrast (Table 4). California burclover was sensitive to tillage, based on the proximity of

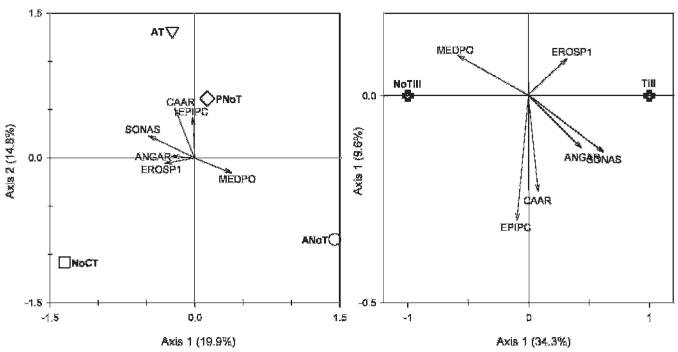

Figure 1. Species-treatment biplots from distance-based redundancy analysis of weed communities in the interrows, with the effects of all four treatments considered separately (A) or grouped according to tillage [till (NoCT + AT) versus no-till (ANoT + PNoT)] (B). Bayer codes represent the following species: scarlet pimpernel (ANGAR), field marigold (CAAR), panicle willowherb (EPIPC), filaree species (EROSP1), California burclover (MEDPO), and spiny sowthistle (SONAS). Species shown are those with a correlation > 0.25 to one of the first two axes. Percent variation explained by each axis is shown in parentheses.

this species' arrow endpoint to ANoT and PNoT or 'NoTill' in both biplots (Figure 1), based on significant treatment and treatment × year effects in ANOVA (Figure 2), and based on significantly higher biomass in no-till versus till treatments (Table 4). California burclover was present in all treatments in 2005, when it had higher biomass (Figure 2) and higher relative abundance in both ANoT and PNoT interrows

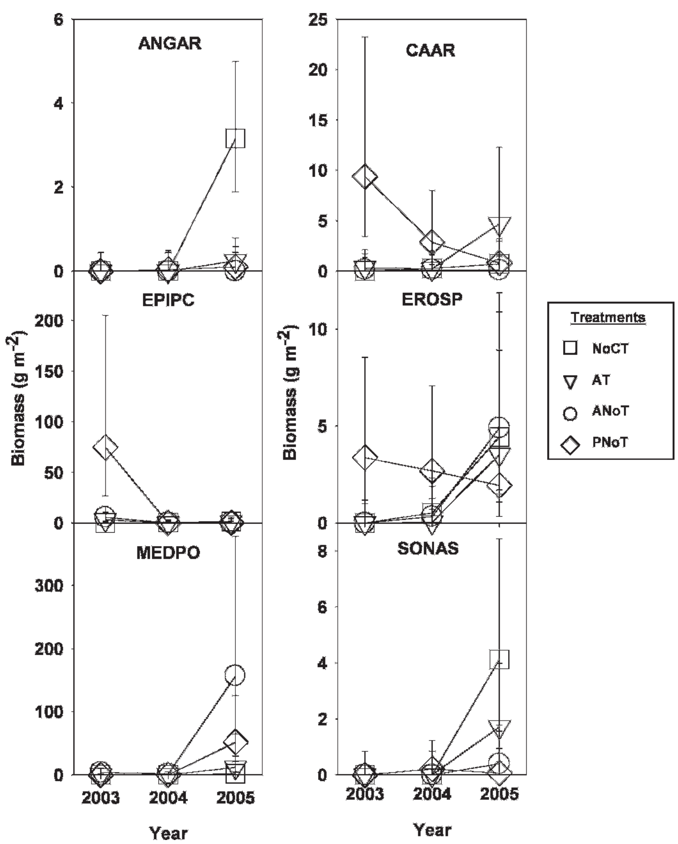

Figure 2. Interrow weeds that were found to have both a correlation > 0.25 to one of the first two axes in distance-based redundancy analysis (Figure 1), and the biomass of which was found to vary significantly among treatments in ANOVA. Each symbol represents the mean of four observations, averaged across blocks. Error bars are 95% confidence intervals; means with overlapping confidence intervals are not significantly different.

Table 4. Responses of selected interrow weeds to tillage, as evaluated by comparing their combined biomass in both tilled treatments (NoCT + AT) to that of both no-till treatments (ANoT + PNoT).[a]

Species[b]	Year	Contrast NoCT + AT vs. ANoT + PNoT
		——— Prob. > *F* ———
Scarlet pimpernel	2003	1.0000
	2004	0.5479
	2005	0.0002
Field marigold	2003	0.7329
	2004	0.0511
	2005	0.0007
Panicle willowherb	2003	0.0029
	2004	0.7927
	2005	0.0010
Filaree	2003	0.0082
	2004	0.1454
	2005	0.9911
California burclover	2003	< 0.0001
	2004	0.0060
	2005	< 0.0001
Spiny sowthistle	2003	0.5698
	2004	0.0939
	2005	0.0141

[a] Abbreviations: NoCT, no cover crop, tilled; AT, annual cover crop, till; ANoT, annual cover crop, no-till; and PNoT, perennial cover crop, no-till.
[b] Species shown are those that had a > 25% correlation to either axis in db-RDA, and had a significant treatment and/or treatment × year effect in ANOVA.

(Table 3). For field marigold, filaree species, and panicle willowherb, associations with individual treatments and/or tillage in the interrows were not consistent over time; these species were associated with tilled treatments in 1-yr and no-till treatments in another (Figure 2, Table 3). It is possible that variation in biomass of field marigold, filaree species, and panicle willowherb is explained, in part, by some factor other than or addition to tillage.

Our findings of significant effects of tillage on weed community structure are supported by past reports on the effects of tillage on weeds, and by reports on the effects of tillage on the individual species we identified as having treatment associations. Tillage changes the vertical distribution of seeds in the soil and increases warming at greater depths, thereby affecting depth of recruitment, such that no-till systems tend to have a significantly more shallow depth of recruitment than tilled systems (du Croix Sissons et al. 2000; Dyer 1995; Soriano et al. 1968). In no-till systems, in contrast, seeds remain on the soil surface and, consequently, are exposed to potential adverse conditions that decrease or increase germination, depending on the species (Chauhan et al. 2006). The association of spiny sowthistle with the till treatments supports previous reports of a relationship between sowthistles and tillage in vineyards (Baumgartner et al. 2005, 2007) and annual crops (Critchley et al. 2006; Puricelli and Tuesca 2005). Our finding of a relationship between California burclover and the no-till treatments is supported by its previously documented sensitivity to tillage (DiTomaso and Healy 2007). Based on the fact that scarlet pimpernel seeds are not carried by wind and are known survive for long periods of time in the seed bank (DiTomaso and Healy 2007), it is possible that the presence of tillage encouraged its recruitment from the seed bank in the tilled interrows.

The db-RDA analyses revealed no significant effects of the cover-crop systems on weed community structure in the intrarows when the systems were treated as four separate

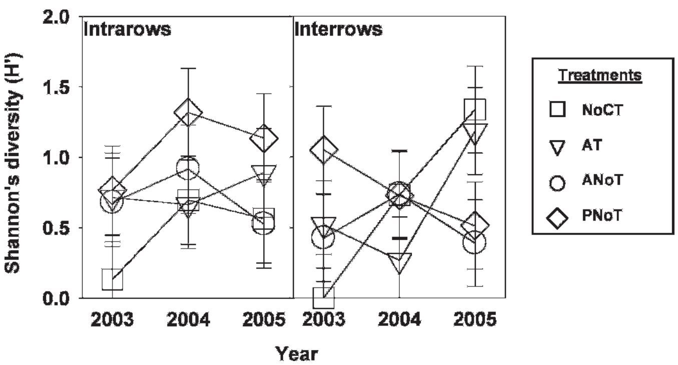

Figure 3. Temporal changes in species diversity in intrarows and interrows. Each symbol represents the mean of four observations, as calculated minus the cover crops, averaged across blocks. Error bars are 95% confidence intervals; means with overlapping confidence intervals are not significantly different.

treatments (P = 0.1) or when grouped according to tillage (P = 0.3). Species that were either favored by tillage (spiny sowthistle and scarlet pimpernel) or were sensitive to tillage (California burclover) in the interrows did not show the same relationships in the intrarows, based on no consistent trends in their biomass in the same treatment (Table 2). As the cover-crop treatments were carried out in the adjacent interrows, we might expect their effects on the intrarows to be somewhat limited, especially given the extremely low weed biomass in the intrarows throughout the study (Table 1).

Species Diversity. In the intrarows, *S* did not vary among treatments (P = 0.1) or years (P = 0.2). *H′* did vary among treatments (P = 0.0004) and years (P = 0.02), but means comparisons following ANOVA showed no significant treatment differences in intrarow *H′* (Figure 3). In the interrows, there were no treatment differences in *S* (P = 0.1), but there were significant changes over time (P < 0.0001). *S* was comparable in 2003 to 2004 (3.19 versus 3.75, $n = 4$), then increased significantly in 2005 in all interrows (6.19, $n = 4$), an event that coincided with a substantial increase in interrow weed biomass (Table 1). *H′* in the interrows was affected by a significant treatment × year interaction (P < 0.0001), such that the no-till treatments had increasing diversity over time, and the tilled treatments had decreasing diversity (Figure 3). Orthogonal contrasts verified these trends, with significantly lower diversity in the tilled interrows in 2003 (P < 0.0001) changing to significantly higher diversity in 2005 (P < 0.0001). Increasing *H′* in the NoCT interrows corresponded to decreasing dominance by one or two species (e.g., birdsrape mustard was the only species present in 2003; Table 3).

Our finding of increasing species diversity over time in the tilled interrows is in contrast to that of past studies showing that more intensively managed annual systems typically have decreases in diversity, as compared to their low-input counterparts, in response to increased herbicide inputs or tillage intensity (Barberì and Mazzoncini 2001; Hyvönen and Salonen 2002; Mas and Verdù 2003; Ngouajio and McGiffen 2002). This may be a function of past cover-cropping practices at the study site. Since vineyard establishment, this site was planted with the no-till, self-seeding annual grass, zorro fescue. It is possible that in the interrows in which the tilled treatments were imposed, weeds were recruited from the dense seed bank that built up over the many preceding years that the vineyard was no till. In the interrows in which no-till treatments were imposed, the lack of tillage and the presence of planted cover crops may have reduced germination of weeds from the seedbank.

Impacts on Production. The cover-crop systems had no effects on vine yield or growth. Yield varied over time (P > 0.0001), with the highest levels in 2005 (6.57 kg vine^{-1}, $n = 4$) and the lowest in 2004 (4.29 kg vine^{-1}, $n = 4$). There were no yield differences due to treatment (P = 0.7) or treatment × year (P = 0.1). Pruning weights varied over time (P > 0.0001), with the highest levels in 2005 (0.68 kg vine^{-1}, $n = 4$) and the lowest in 2004 (0.56 kg vine^{-1}, $n = 4$). There were no pruning weight differences due to treatment (P = 0.2) or treatment × year (P = 0.7).

Previous research on vineyard cover crops in Mediterranean regions has focused primarily on production impacts, as the potential for water stress and/or soil mineral nutrients due to competition from cover crops is relatively high (Ingels et al. 2005; Tesic et al. 2007). Although the cover crops we examined consisted of winter annuals and perennials that reached peak biomass at the time of the growing season when vine growth is most rapid (between budbreak and bloom; Mullins et al. 1992), our findings of no significant differences in yield or growth among treatments suggest that there was no competition between the vines and the cover crops. This may be due to a combination of the site's soil type, which holds sufficient moisture well into summer (hence the need for weekly irrigation that did not begin until July), and the relatively low yields demanded of the vines. Wine grape production is a somewhat unique cropping system in that *N* inputs are minimized to purposely limit shoot growth (Perret et al. 1983), and water stress is imposed to enhance wine composition (Matthews et al. 1990). In addition, many growers thin clusters to one or two per shoot, between fruit set and veraison, in order to improve the quality of the remaining clusters (Keller et al. 2005).

The cover-crop systems had a significant effect on vine mineral nutrition. Petiole N and K were the only mineral nutrients that differed among treatments (P = 0.01 and P = 0.0004, respectively). The lowest levels of total N were in the no-till treatments, PNoT and ANoT (8.8 and 9.0 mg, respectively), compared to the highest in the tilled treatments, AT and NoCT (9.7 and 10.2 mg, respectively). The lowest levels of total K were from NoCT and PNoT (19.7 and 20.4 mg, respectively), compared to the highest in the annual cover-crop treatments, AT and ANoT (21.5 mg and 22.5 mg, respectively). In spite of statistically significant differences, however, lower petiole N in PNoT and ANoT, and lower petiole K in NoCT and PNoT were within adequate levels (Christensen et al. 1978). Temporal changes in petiole P were not consistent among treatments (treatment × year interaction, P = 0.03), but means comparisons following ANOVA showed no significant differences among treatments within years (data not shown). Petiole B and Zn varied over time (P = 0.02 and P < 0.0001, respectively), but not among treatments (P = 0.9 and P = 3, respectively). Annual means averaged across treatments ($n = 4$ per year) ranged from 7.9 to 11.0 mg total N, 6.9 to 7.6 mg total P, 20.3 to 21.7 mg total K, 41.8 to 43.5 µg B, and 100.4 to 304.6 µg Zn g dry petiole^{-1}.

The cover-crop systems had no effects on soil mineral nutrition or physical properties. Soil total N, Olsen P, X-Ca, and X-Na varied among years ($P < 0.0001$, $P = 0.0001$, $P = 0.02$, $P < 0.0001$, respectively), but not between intrarows and interrows or among treatments (data not shown). Annual means averaged across treatments and locations ($n = 8$ per year) ranged from 1.6 to 1.8 mg total N, 17.1 to 21.9 μg Olsen P, 134.2 to 140.5 μmol X-Ca, and 1.8 to 2.4 μmol X-Na g dry soil^{-1}. There were no significant effects on the remaining soil parameters (data not shown). Annual means averaged across treatments and locations for these parameters ($n = 8$ per year) ranged from 19.0 to 19.6 mg total C, 7.3 to 7.7 μmol X-K, 129.6 to 132.9 μmol X-Mg, 389.8 to 398.8 μmol cation exchange capacity, and 20.9 to 24.1 mg organic matter g dry soil^{-1}.

Management Implications. Our findings of significant differences in weed biomass and diversity in the interrows, coupled with unique species-treatment associations for several species, demonstrate that cover-cropping practices clearly impact weed communities in the interrows. The impacts of the cover-crop systems on weed communities in the adjacent intrarows, however, were minimal in our study. If glyphosate had not been used to control weeds in the intrarows, our findings may have been different. Weed control in organic vineyards is achieved primarily through intrarow soil cultivation, and it is possible that the species we found to be favored by tillage in the interrows (spiny sowthistle and scarlet pimpernel) might be encouraged by tilling in the intrarows. Spiny sowthistle, in particular, is a problematic vineyard weed, in that it grows into the vine canopy and interferes with harvest (Lanini and Bendixen 1992). Nonetheless, our finding of no significant effects of the cover-crop systems on intrarow weeds suggests that the specific practices we evaluated are unlikely to interfere with chemical weed control beneath the vines. As dormant-season cover crops in California vineyards are planted primarily to reduce soil erosion from winter rains, our findings of no significant yield, growth, or nutrition effects suggest that cover-crop management systems are also unlikely to have negative impacts on vine health.

Sources of Materials

[1] Roundup UltraMax, Monsanto Company, 800 North Lindbergh Boulevard, St. Louis, MO 63167.

[2] PC-ORD Version 4.0 statistical software, MjM Software Design, PO Box 129, Gleneden Beach, OR 97388.

[3] SAS Version 8.2 statistical software, SAS Institute, Inc., SAS Campus Drive, Cary, NC 27513.

[4] CANOCO Version 4.5 statistical software, Plant Research International, P.O. Box 16, 6700 AA Wageningen, The Netherlands.

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